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FIRE PROPAGATION IN CONCURRENT FLOWS, FINAL PROGRESS REPORT

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Prepared for
U.S. DEPARTMENT OF COMMERCE
National Institute of Standards
and Technology
National Engineering Laboratory
Center for Fire Research
Gaithersburg, MD 20899

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Robert A. Mosbacher, Secretary
NATIONAL INSTITUTE OF STANDARDS
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Raymond G. Kammer, Acting Director

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Notice

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FIRE PROPAGATION IN CONCURRENT FLOWS

NBS Grant No. 60NANB7D0737

Final Progress Report

August 1, 1988 - July 31, 1989

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ABSTRACT

A research program is being carried out to study the mechanisms controlling the spread of fire in a forced gas flow. Particular emphasis is given to the case when the gas flow is concurrent with the direction of fire spread.

The research tasks completed during this reporting period include an experimental study of the effect on the flame spread rate of the turbulence intensity of a concurrent air flow, and a theoretical analysis of the effect of a prescribed gas velocity profile on the flame spread rate predictions. The results of the experiments show that for flames spreading over thick PMMA sheets, the flame spread process is significantly affected by the flow turbulence intensity. For a fixed flow velocity, the flame spread rate decreases as the turbulent intensity is increased. This appears to be mainly due to the shortening of the flame length. Schlieren images of the process indicate that the decrease of the flame length may be the result of the intense entrainment of cold air in the flame at the higher turbulent intensities. The results of the theoretical analysis indicate that the gas velocity profile influences strongly the flame spread rate predictions.

I. INTRODUCTION

The spread of flames over a combustible material plays an important role in the early development of a fire. The rate of flame spread determines the rates of fuel involvement and heat released in the developing fire, and consequently its growth. The transfer of heat from the flame to the unburnt fuel is one of the controlling mechanisms of flame spread. In the concurrent mode of flame spread, the flames are pushed ahead of the burning region by the gas flow, which facilitates the transfer of heat from the flame to the unburnt material. As a consequence, this mode of spread is very fast and hazardous because it causes the rapid involvement of the combustible materials in the fire. Concurrent flame spread typically occurs during the upward spread of fire along walls, and in floors and ceilings of corridors with air currents moving in the direction of flame spread.

In most practical cases the spread of fire occurs under turbulent flow conditions. Flow turbulence can affect both the heat transfer and the chemical kinetic mechanisms that control the flame spread process. The determination of the role of these mechanisms is necessary to understand and predict the spread of fire under realistic conditions.

Research carried out during this reporting period include the experimental observation of the flow turbulence intensity effect on the flame structure and its rate of spread, and the theoretical prediction of the gas velocity profile effect on the rate of flame spread. The research progress made during this reporting grant period is summarized below.

II. RESEARCH PROGRESS

II.1 Experiments of Flame Spread in a Concurrent Turbulent Flow

An experimental study has been conducted of the influence on the spread of flames over the surface of PMMA sheets of the turbulence intensity of an air flow in the same direction of flame propagation. The experiments are carried out in a facility specifically designed to perform flame spread experiments consisting of a small scale combustion wind tunnel and supporting instrumentation based primarily on optical and thermocouple measuring methods. The turbulence intensity in the tunnel test section is varied by means of grids and perforated plates of different sizes placed at the exit of the tunnel converging nozzle. The velocity and turbulence intensity of the flow field are measured with a one component Laser Doppler Velocimeter. The flame spread rate is measured from the surface temperature history as given by thermocouples embedded at fixed intervals along the fuel surface. A Schlieren system is used to provide qualitative information about the effect of the flow turbulence on the flame and thermal layer structure. The fuel specimens are 6 in. wide, 12 in. long and 0.5 in. thick PMMA sheets and the oxidizing gas is air. Tests are conducted for flow velocity ranging from 1 to 4 m/sec with turbulence intensity varying from 1 to 20%.

The measurements of the flame spread rate over PMMA sheets as a function of the concurrent air flow velocity are shown in Fig. 1 for several values of the turbulence intensity. It is seen that the spread rate increases approximately linearly with the flow velocity. The slope decreases as the turbulence intensity decreases. The dependence of the concurrent flame spread rate on the turbulence intensity is presented in Fig. 2. It is seen that the spread rate decreases as the turbulence intensity increases, and that the effect is more pronounced for larger flow velocities. These results are very interesting and somewhat surprising since this mode of flame spread is controlled by heat transfer from the flame to the fuel, and it is well known that turbulent boundary layer heat transfer is larger than the laminar flow one. The results, which appear to be due to a strong effect of the turbulence intensity on the flame length, are very important not only because they introduce new aspects about the flame spread process not previously predicted, but because it may have significant influence in the application of flame spread formulas in models of room fire development.

The mechanisms by which turbulence affects the flame spread rate can be inferred from the theoretical analysis of the spread process. A simplified heat transfer model of the flame spread provides the following expression for the rate of spread (Saito, L., quintiere, J. and Williams, F.A., 1st Int. Symp. Fire Safety Sci. 75, 1986).

$$v_f = q^2\, l_f/(k\rho c\, (T_p - T_i))^2 \qquad (1)$$

where q is the surface heat flux, l_f the flame length, kρc are the thermal properties of the solid and T_p and T_i the solid pyrolysis and initial temperatures respectively. The flow velocity and turbulence intensity can affect both q and l_f and through them the flame spread rate. Thus, it is important to determine how turbulence affects these parameters. In the work performed to date, we have not measured these effects directly. However, it is possible to deduce them approximately from the surface temperature histories. The flame length is determined with the spread rate and the time required for the surface temperature at a thermocouple position to rise from ambient to the pyrolysis value. The surface heat flux is calculated from the time variation of the surface temperature by assuming that the fuel behaves as a semi-infinite solid.

The calculated variation of the flame length with the flow velocity and turbulence intensity are presented in Figs. 3 and 4 respectively. It is seen that the dependence of the flame length on the flow velocity is different depending on the turbulence intensity. For low turbulence intensities, the flame length increases with the flow velocity and for large turbulence intensities, it decreases. This effect seems to be due primarily to the convective cooling of the reaction zone by the cold air induced toward the flame by the turbulent eddies.

In order to obtain more information about the mechanisms causing the shortening of the flame length with the turbulence intensity, a Schlieren system was constructed and applied to produce Schlieren images of the flame. The Schlieren system, which was constructed with in house equipment, has a collimated light beam 18" in diameter. It consists of a 750 W Tungston lamp light source, beam expanding and converging lenses and two 18" parabolic mirrors. A characteristic example of the flame images obtained with this system is shown in Fig. 5. It is seen that as the flow turbulence intensity increases, more cold air is introduced into the flame zone and the mixing of the flow becomes more intense. These are the effects that appear to cause the shortening of the flame length with the turbulence intensity.

The calculated variation of the heat flux with the turbulence intensity is shown in Fig. 6. It is seen that the heat flux is only weakly affected by the flow turbulence, decreasing slightly with the turbulence intensity for large flow velocities and increasing slightly for low flow velocities. All of the above results have been combined in Fig. 7 where the ratio V_f/Ul_f (deduced from Eq. (1)) is plotted versus the flow turbulence intensity. It is seen that this ratio is independent of the flow velocity and turbulence intensity, which indicates that the effect of the flow turbulence on the flame spread rate takes place primarily through the flame length and heat flux. This again is a significant result since the prediction of flame length as a function of the problem parameters is an important factor in the development of room fires.

The verification of these preliminary observations is important and will be one of the research tasks of the continuation research program.

II.2 Analysis of the Gas Velocity Profile Effect on the Theoretically Predicted Flame Spread Rate

The problem considered describes the spread of a flame over the surface of a thermally thick fuel slab in an oxidizing gas flowing in the direction opposite to that of flame propagation. The velocity field is prescribed thus eliminating the need for solving the momentum equation and reducing the problem to the solution of the gas phase equations of energy and species coupled at the interface to the solid phase energy equation. The gas phase chemistry is treated by means of a one step, second order reaction with a reaction rate of the Arrhenius type. The pyrolysis of the fuel is assumed to be given by a zero order Arrhenius rate, which removes the need to use a prescribed surface temperature. The transient, reactive, two-dimensional governing equations and boundary conditions are solved numerically using an implicit numerical scheme with a variable grid. The fuel property values selected, although not specific to any particular fuel, correspond approximately to a cellulose combustible fuel. The calculations are made for two cases of oxygen mass fraction, Yox = 0.23 and Yox = 0.5, and with Oseen and Hagen-Poiseuille velocity profiles. The maximum velocity of the parabolic profile is equal to the constant value of the uniform profile. The Yox = 0.23 case corresponds to a flame spread regime controlled by chemical kinetic effects, and the Yox = 0.5 case to one controlled by heat transfer effects at low flow velocities and chemical kinetic effects at high flow velocities.

Chemically Controlled Regime

The predicted flame spread rate for Yox = 0.23 as a function of the maximum gas velocity are plotted in Fig. 8 for both the Oseen and Hagen-Poiseuille profiles. The model predictions are in qualitative agreement with previous experimental results. It is seen that for the same maximum velocity value the shape of the velocity profile plays a significant role in the predicted spread rate, particularly at higher velocities where spread rates up to 5 times larger are predicted for the Hagen-Poiseuille profile.

The predicted temperature and species distributions presented in Fig. 9 show that the premixed zone at the flame leading edge is larger in the case of the Hagen-Poiseuille profile. Also, the flame is slightly farther away from the surface, which results in a smaller surface temperature and heat flux. Another important difference is the observed position of the flame leading edge with respect to the upstream edge of the solid thermal layer. In the Oseen case the flame leading edge is farther downstream than in the Hagen-Poiseuille case. This is indicative of a weaker (closer to extinction) reaction and is the result of the higher velocities imposed near the fuel surface by the Oseen profile. Although the surface heat flux is larger, the fact that the flame is positioned further downstream results in smaller heat transfer upstream and consequently in a smaller flame spread rate.

Thermally Controlled Regime

The predicted flame spread rates for Yox = 0.5 as a function of the maximum gas velocity are plotted in Fig. 10 for the Oseen and Hagen-Poiseuille profiles. In both cases, the predicted spread rate first increases and then decreases as the flow velocity increases, which is also in qualitative agreement with previous experimental observations. The solutions with the Hagen-Poiseuille profile, however, give better quantitative agreement with the experiments. The higher spread rates predicted with the Oseen profile in the thermal regime (increasing spread rate region) are due to the flame being closer to the surface and the resulting larger heat transfer to the solid. On the other hand, the sharp decrease of the spread rate in the chemically controlled regime is due to the high velocities present near the fuel surface that cause the weakening of the gas phase reaction. This is confirmed by the predicted distributions of gas and solid phase temperature and species concentrations presented in Fig. 11. In the thermal regime the relative position between the flame leading edge and the upstream edge of the solid thermal layers are similar for both profiles, but the flame is closer to the surface for the Oseen case, and both the surface heat flux and temperature are higher. In the chemically controlled regime the flame leading edge is located downstream in the Oseen case, which results in a smaller heat transfer upstream and consequently in a smaller spread rate.

II.3 Publications and Presentations

Amos, B., Kodama, H. and Fernandez-Pello, A.C., "An Analysis of the Ignition by Vapor Radiation Absorption of Vaporizing Fuel at Zero Gravity," *Progress in Astronautics and Aeronautics,* 113, p. 115 (1988).

Amos, B. and Fernandez-Pello, A.C., "Ignition and Flame Development of a Vaporizing Combustible Surface in a Stagnation Point Flow," *Combustion Science and Technology,* 62, 4-6, p. 331 (1988).

Di Blasi, C., Crescitelli, S., Russo, G., and Fernandez-Pello, A.C., "Predictions of the Dependence on the Opposed Flow Characteristics of the Flame Spread Rate Over Thick Solid Fuels," *2nd International Symposium on Fire Safety Science,* p. 119, (1988).

Di Blasi, C., Crescitelli, S., Russo, G., and Fernandez-Pello, A.C., "Model of the Flow Assisted Spread of Flames Over a Thin Charring Combustible," *22nd International Symposium on Combustion,* The Combustion Institute, p. 1205, (1988).

Zhou, L., Fernandez-Pello, A.C., and Cheng, R., "Flame Spread in an Opposed Turbulent Flow," submitted for publication in Combustion and Flame, (1988).

Di Blasi, C., Crescitelli, S., Russo, G., and Fernandez-Pello, A.C., "On the Influence of the Gas Velocity Profile on the Theoretically Predicted Opposed Flow Flame Spread," *Combustion Science and Technology,* 64, p. 289, (1989).

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10. Predicted dependence of the opposed flame spread rate on the flow velocity for Yox = 0.5.
11. Predicted temperature and species concentration fields for Yox = 0.5.

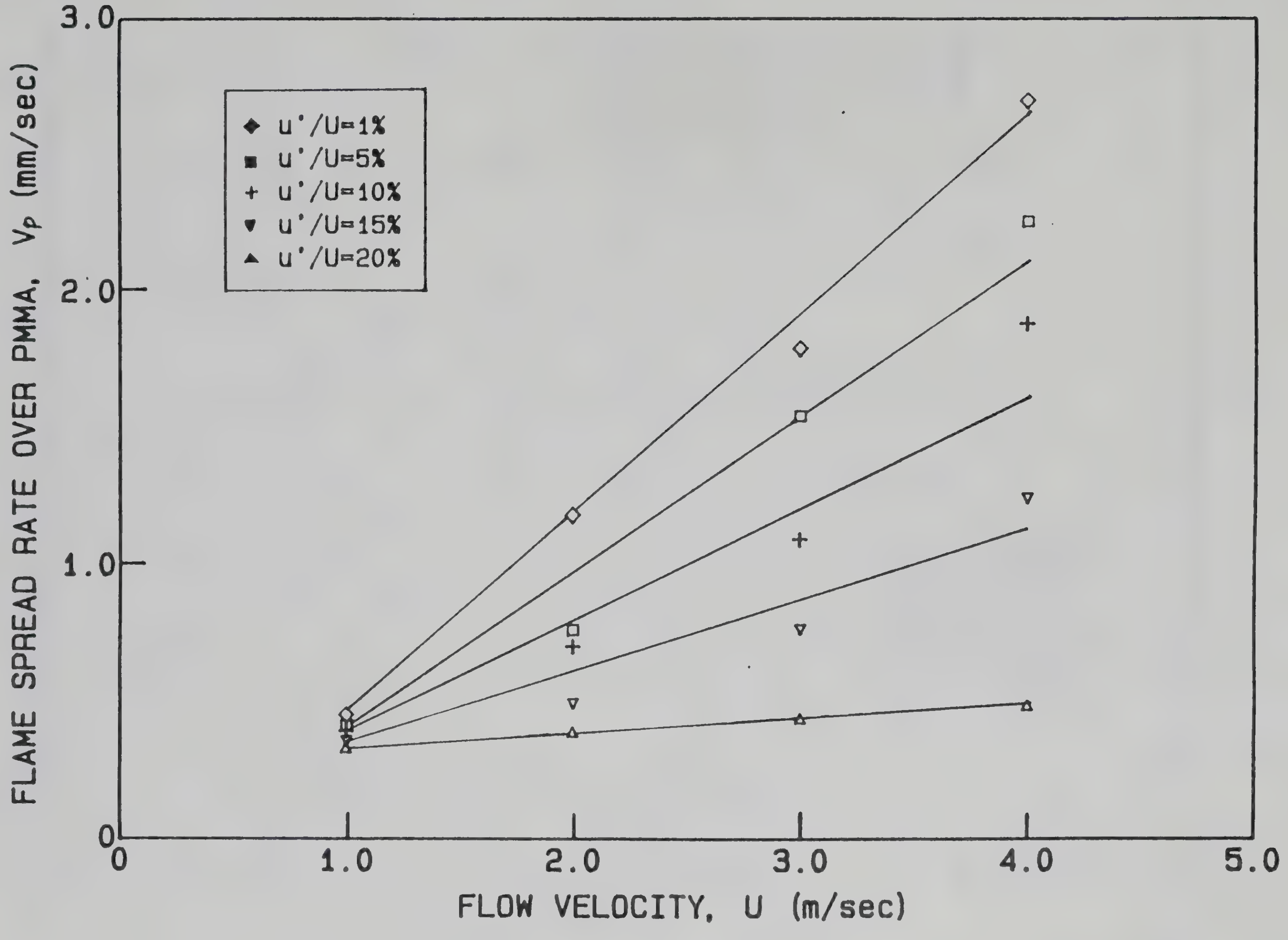

3.0
2.0
1.0
0
FLAME SPREAD RATE OVER PMMA, V_p (mm/sec)
0
1.0
2.0
3.0
4.0
5.0
FLOW VELOCITY, U (m/sec)
◆ u'/U=1%
■ u'/U=5%
+ u'/U=10%
▼ u'/U=15%
▲ u'/U=20%

Figure 1.

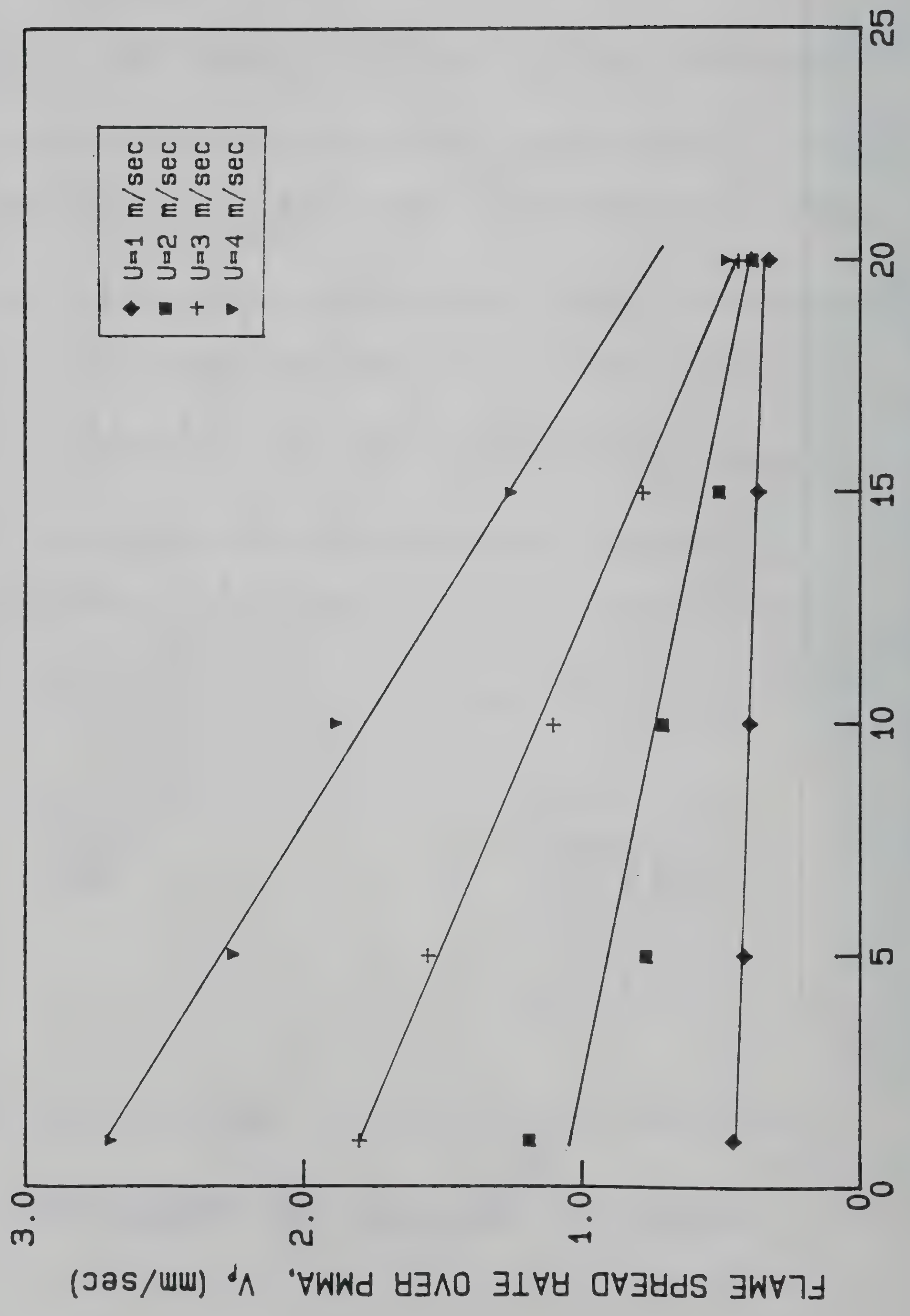

FLAME SPREAD RATE OVER PMMA, V_f (mm/sec)
3.0
2.0
1.0
0
TURBULENCE INTENSITY, u'/U (%)
0
5
10
15
20
25
◆ U=1 m/sec
■ U=2 m/sec
+ U=3 m/sec
▼ U=4 m/sec

Figure 2.

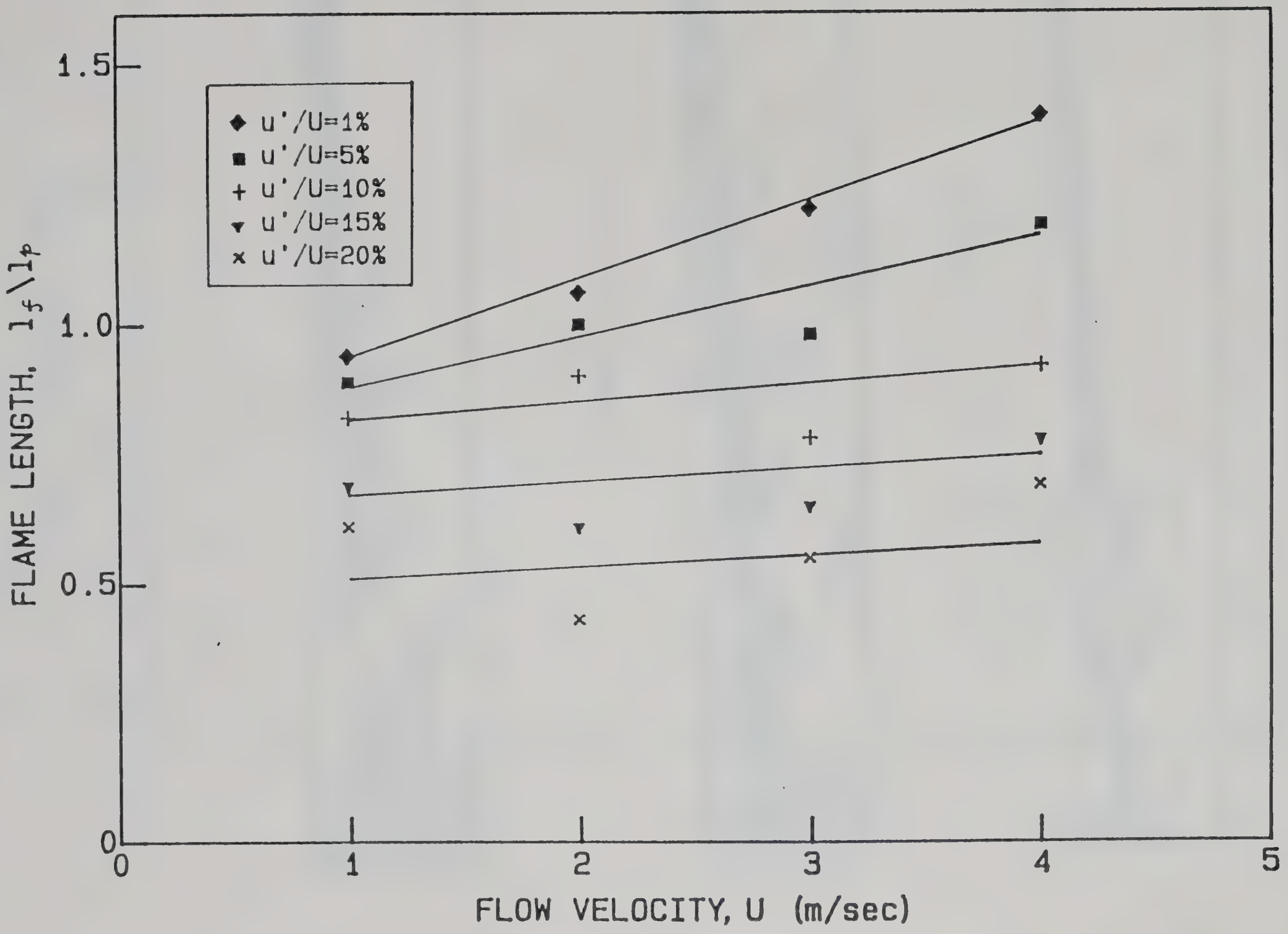

u'/U=1%
u'/U=5%
u'/U=10%
u'/U=15%
u'/U=20%
FLAME LENGTH, $l_f \backslash l_p$
1.5
1.0
0.5
0
0
1
2
3
4
5
FLOW VELOCITY, U (m/sec)

Figure 3.

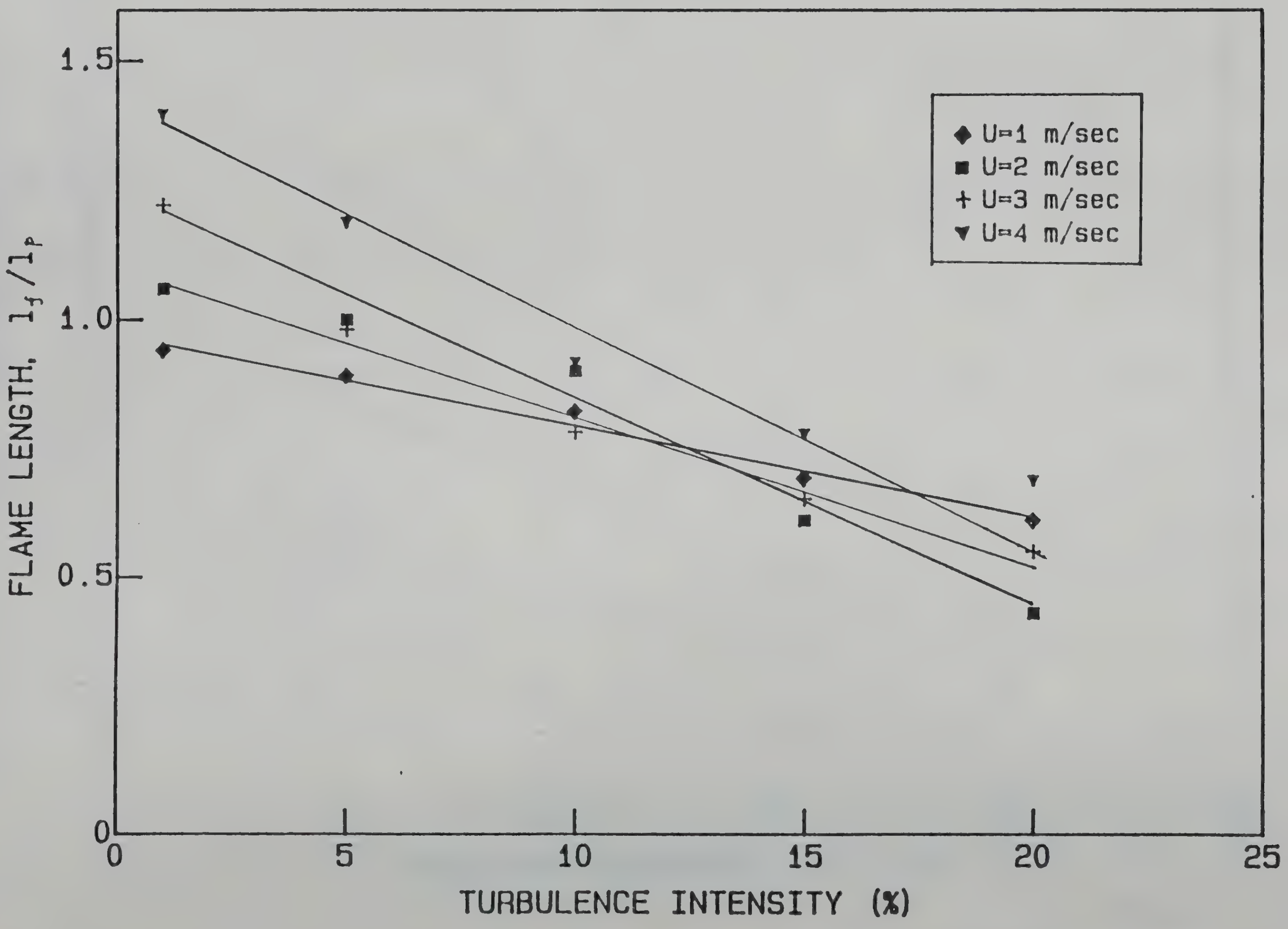
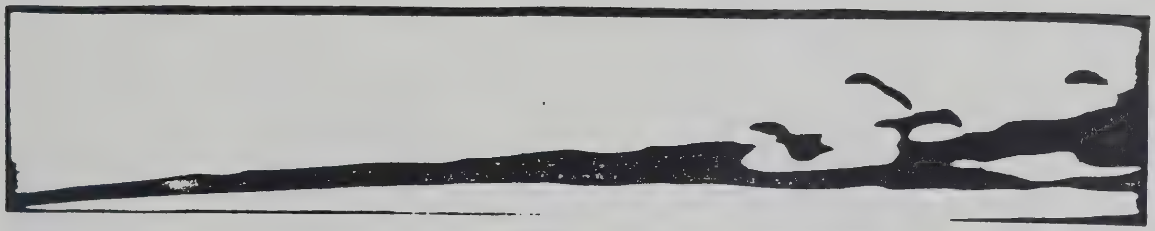
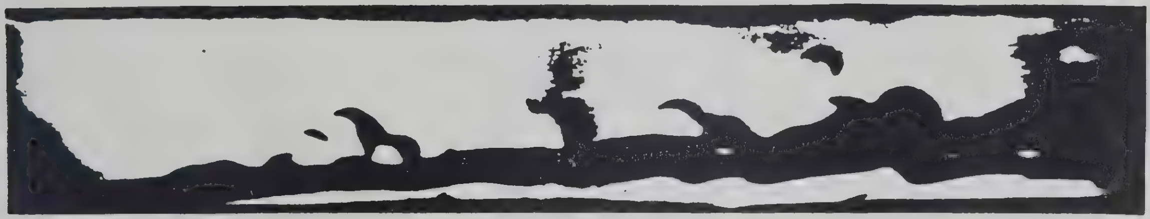

1.5
1.0
0.5
0
0
5
10
15
20
25
FLAME LENGTH, l_f/l_p
TURBULENCE INTENSITY (%)
◆ U=1 m/sec
■ U=2 m/sec
+ U=3 m/sec
▼ U=4 m/sec

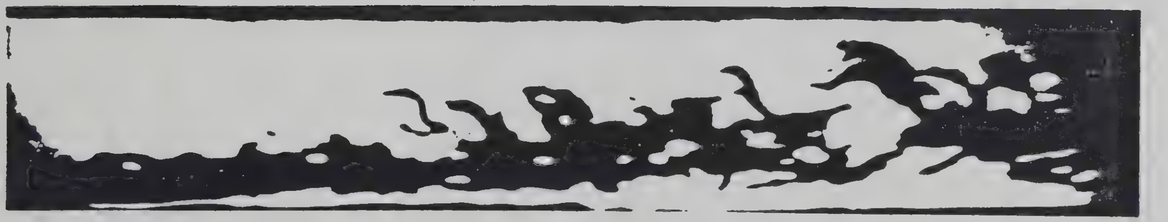
Figure 4.



U = 3 m/sec u'/U = 1%



U = 3 m/sec u'/U = 5%



U = 3 m/sec u'/U = 15%

Figure 5.

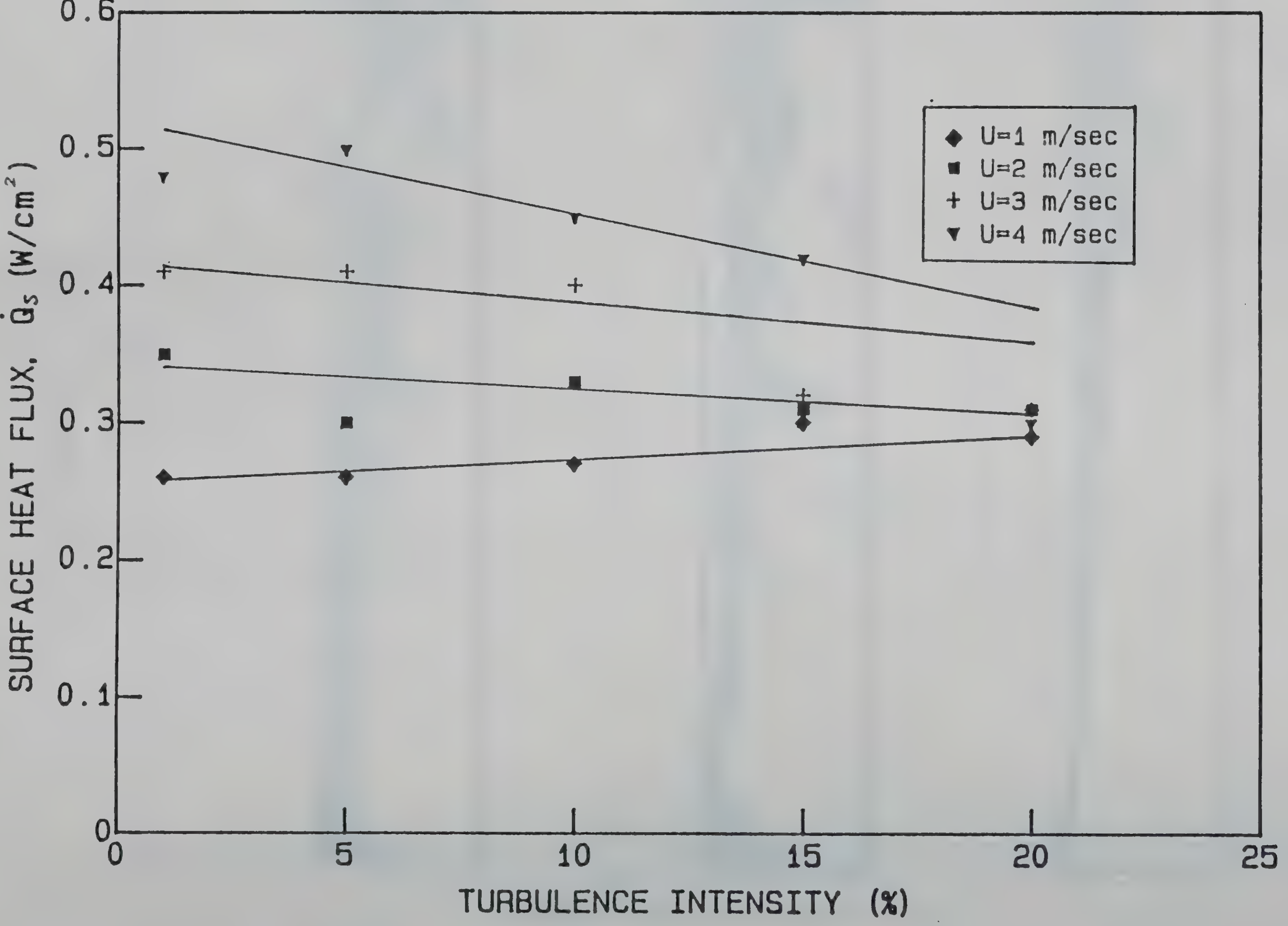

0.6
0.5
0.4
0.3
0.2
0.1
0
SURFACE HEAT FLUX, $\dot{Q}_s$ (W/cm^2)
0
5
10
15
20
25
TURBULENCE INTENSITY (%)
◆ U=1 m/sec
■ U=2 m/sec
+ U=3 m/sec
▼ U=4 m/sec

Figure 6.

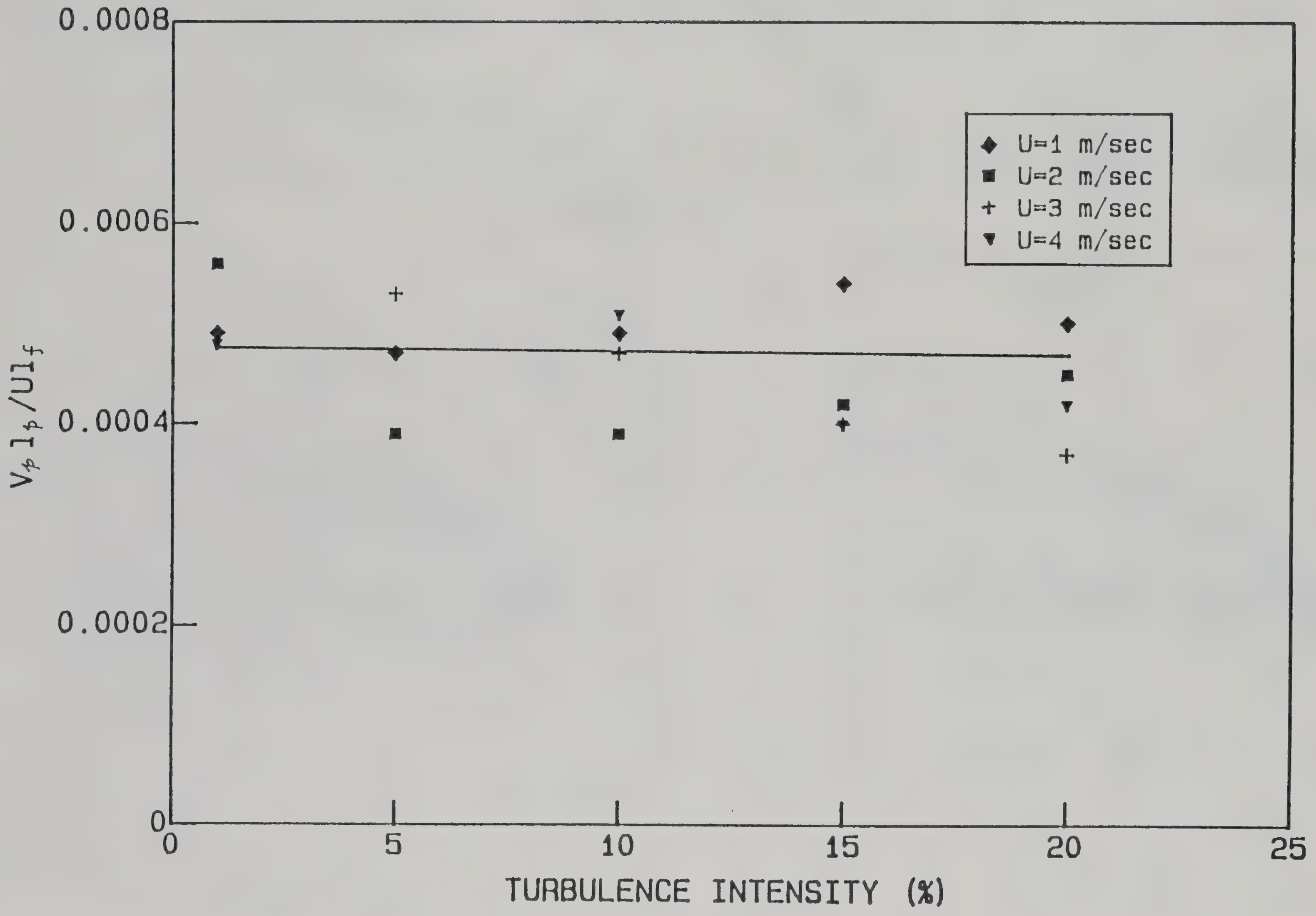

0.0008
0.0006
0.0004
0.0002
0
0
5
10
15
20
25
$V_\phi l_\phi / U l_f$
TURBULENCE INTENSITY (%)
◆ U=1 m/sec
■ U=2 m/sec
+ U=3 m/sec
▼ U=4 m/sec

Figure 7.

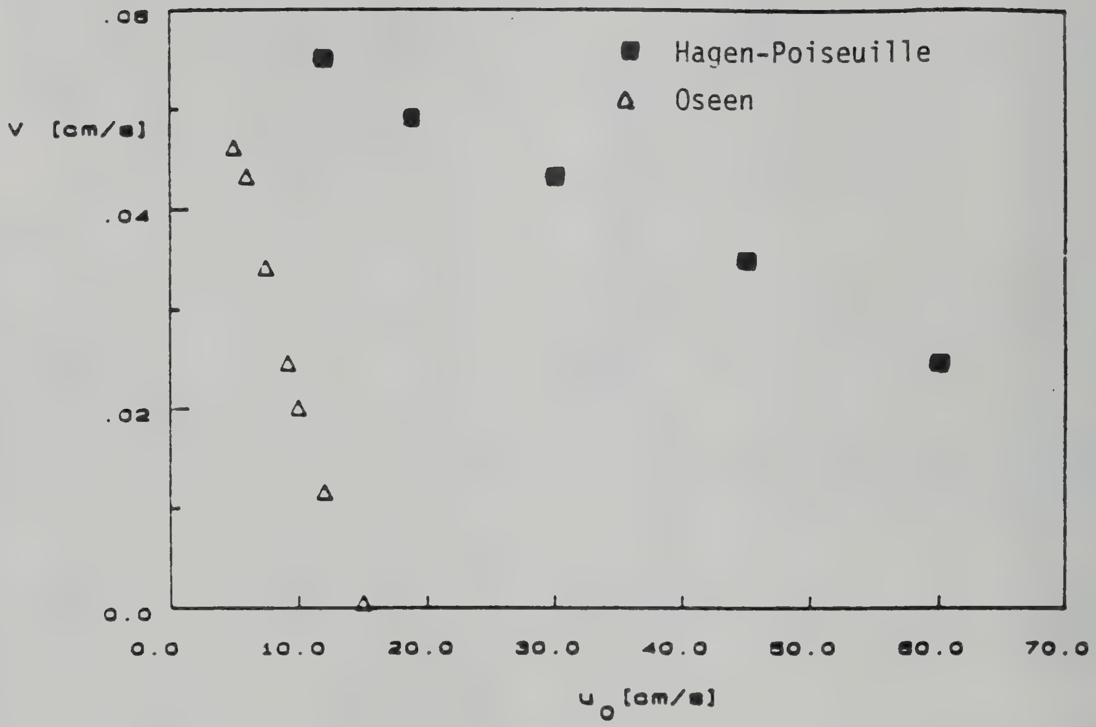
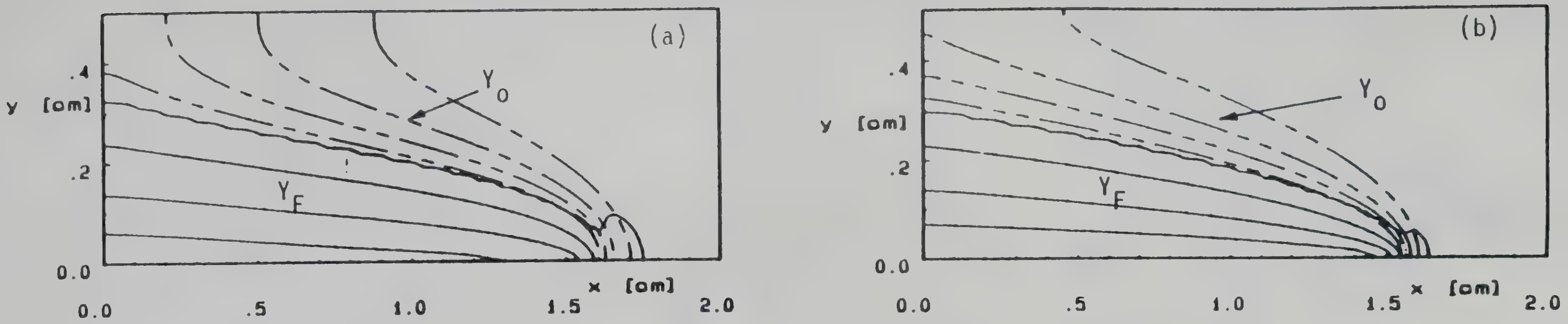
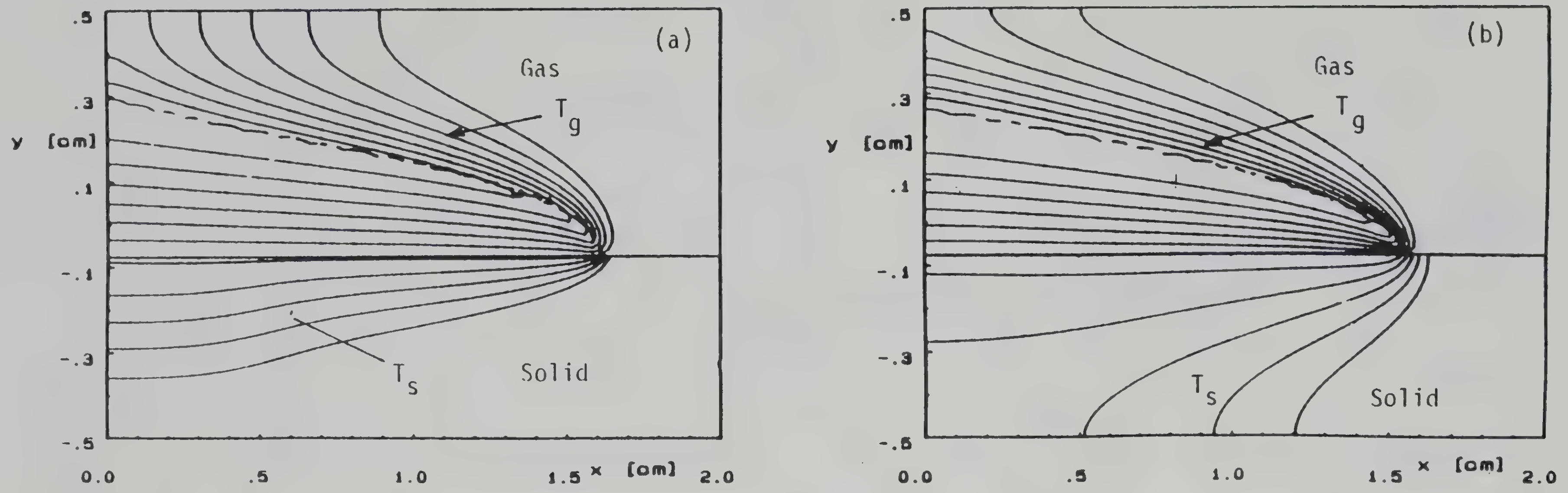

.06
V [cm/s]
.04
.02
0.0
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
u$_0$ [cm/s]
■ Hagen-Poiseuille
Δ Oseen

Figure 8.



a. Species

b. Species



a. Temperature

b. Temperature

Figure 9.

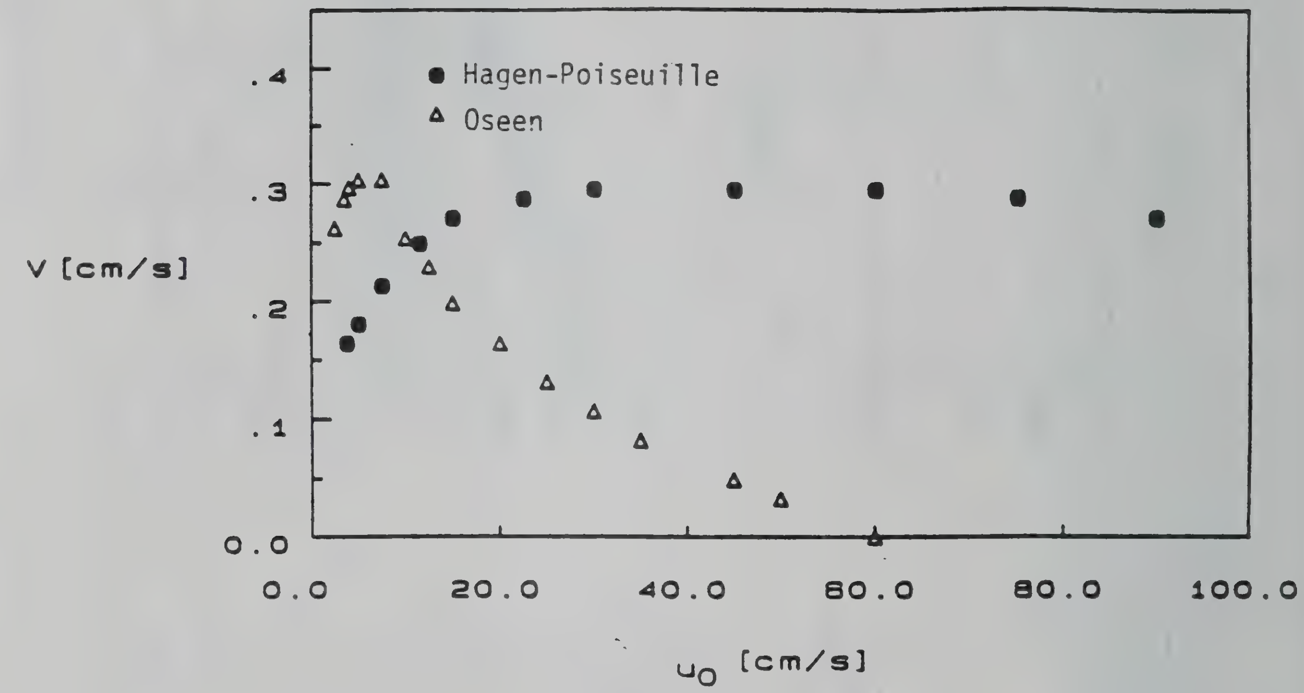
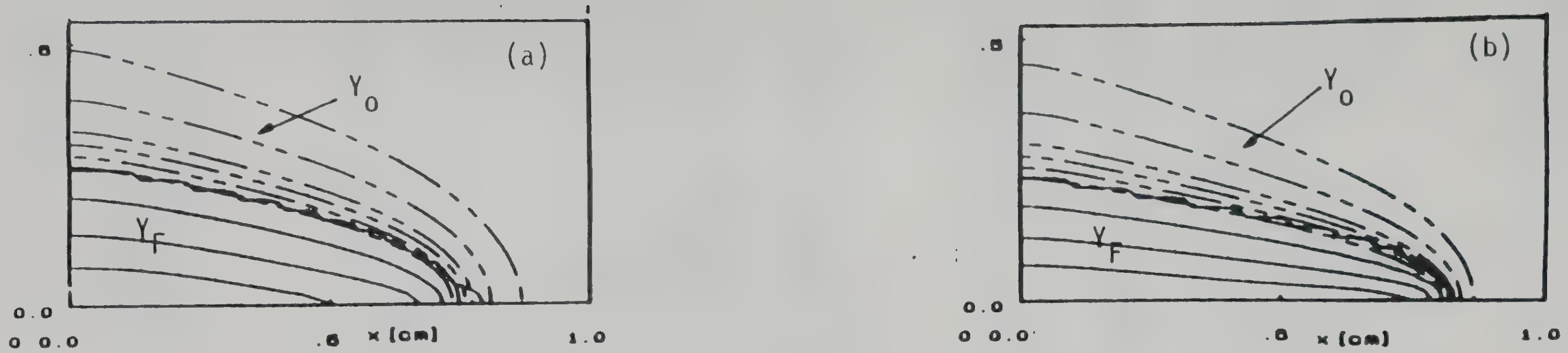
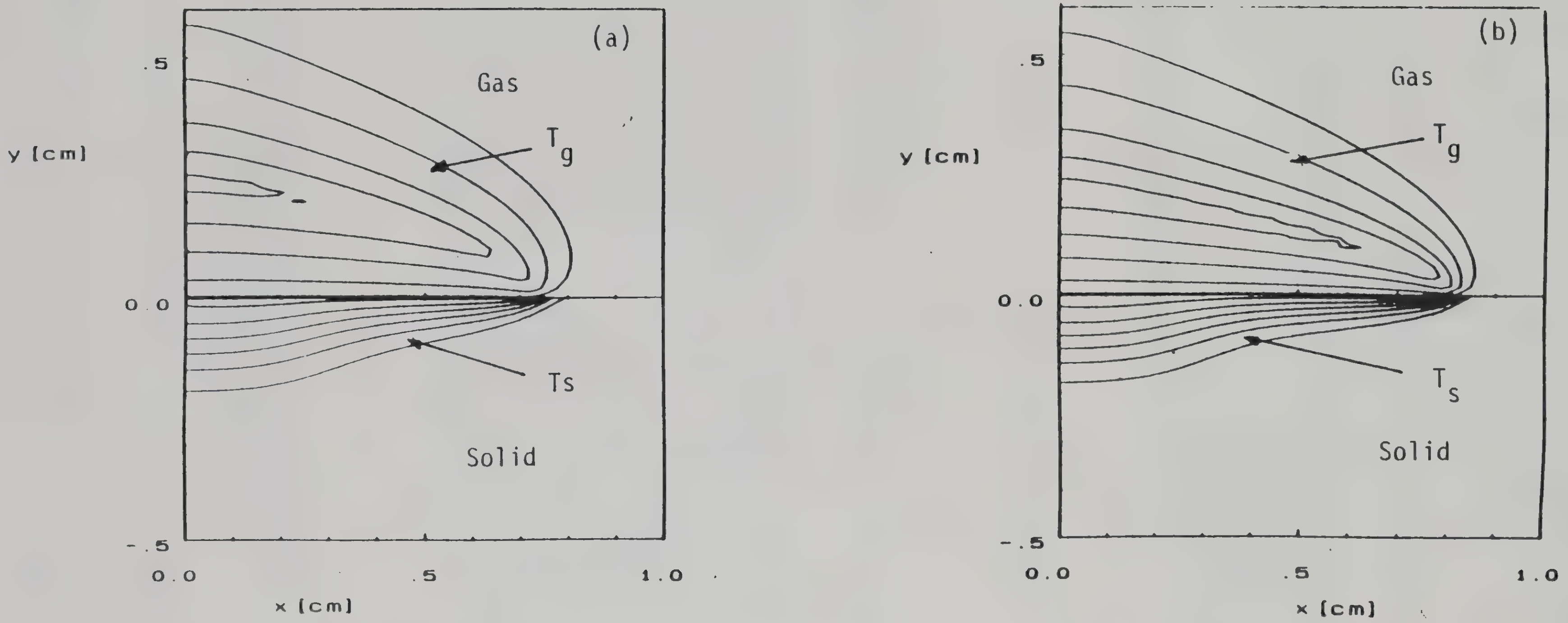

● Hagen-Poiseuille
Δ Oseen
V [cm/s]
.4
.3
.2
.1
0.0
0.0
20.0
40.0
60.0
80.0
100.0
u_0 [cm/s]

Figure 10.



a. Species b. Species



a. Temperature b. Temperature

Figure 11.

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A research program is being carried out to study the mechanisms controlling the spread of fire in a forced gas flow. Particular emphasis is given to the case when the gas flow is concurrent with the direction of fire spread. The research tasks completed during this reporting period include an experimental study of the effect on the flame spread rate of the turbulence intensity of a concurrent air flow, and a theoretical analysis of the effect of a prescribed gas velocity profile on the flame spread rate predictions. The results of the experiments show that for flames spreading over thick PMMA sheets, the flame spread process is significantly affected by the show turbulence intensity. For a fixed flow velocity, the flame spread rate decreases as the turbulent intensity is increased. This appears to be mainly due to the shortening of the flame length. Schlieren images of the process indicate that the decrease of the flame length may be the result of the intense entrainment of cold air in the flame at the higher turbulent intensities. The results of the theoretical analysis indicate that the gas velocity profile influences strongly the flame spread rate predictions.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

air flow; flame length; flame spread; polymethylmethacrylate; pyrolysis

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